Attentional facilitation of detection of flicker on moving objects

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We investigated the influence of attention and motion on the sensitivity of flicker detection for a target among distractors. Experiment 1 showed that when the target and distractors were moving, detection performance plummeted compared to when they were not moving, suggesting that the most sensitive detectors were local, temporal frequency-tuned receptive fields. With the stimuli in motion, a qualitatively different strategy was required and this led to much reduced performance. Cueing, which specified the target location with 100% validity, had no effect for targets that had little or no motion, suggesting that the flicker was sufficiently salient in this case to attract attention to the target without requiring any search. For targets with medium to high speeds, however, cueing provided a strong increase in sensitivity over uncued performance. This suggests a significant advantage for localizing and tracking the target and so sampling the luminance changes from only one trajectory. Experiment 2 showed that effect of attention was to increase the efficiency and duration of signal integration for the moving target. Overall, the results show that flicker sensitivity for a moving target relies on a much less efficient process than detection of static flicker, and that this less efficient process is facilitated when attention can select the relevant trajectory and ignore the others.

Introduction

Human vision shows exquisite sensitivity to transient changes in luminance, and this is critical for dealing with and orienting to dynamic changes in the visual scene. For example, an observer can discriminate between a steady and a flickering stimulus with only 0.5% modulation of the test luminance (de Lange, 1958; Kelly, 1984; Robson, 1966). It is assumed that this high level of performance is mediated by magnocellular units that have peak sensitivity at around 8 Hz (Livingstone & Hubel, 1988; Merigan & Maunsell, 1993). This sensitivity drops in the periphery, but if the size of the flickering test is scaled with eccentricity, then there is not much loss (Virsu, Rovamo, Laurinen, & Nasanen, 1982).

However, the salient changes in our visual environment do not often occur on conveniently immobile tests. They typically occur on moving stimuli, moving either because of their own displacement or because of our eye, head, or body movements. A moving stimulus presents a very different challenge to the visual system. If the detection of flicker depends on the responses of cells tuned to the temporal frequency of the test, then a stimulus that moves over the retina may not stay long enough within one receptive field for that flicker to be detected. There are, of course, other modes by which the flicker of a moving stimulus could be detected (e.g., the detection of an absolute difference in luminance of the stimulus at two points along its trajectory or the detection of gradual change in luminance of the stimulus), but the detection mediated by units with fixed receptive fields is plausibly the most sensitive, or at least the best understood at the moment (DeAngelis, Ohzawa, & Freeman, 1993; Frishman, Freeman, Troy, Schweitzer-Tong, & Enroth-Cugell, 1987; Tan & Yao,

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2009). The purpose of this paper is to better understand visual sensitivity to dynamic changes of moving targets and to determine the role of attention in this sensitivity.

Indeed, the motion of a target can cause the reduction of sensitivity to its flicker, and one of the most dramatic effects is motion silencing, where the random flickering of disks in a ring becomes virtually undetectable when the ring of disks is set in rotation (Suchow & Alvarez, 2011). In addition to their demonstration, Suchow and Alvarez (2011) reported a reduction in the detection of rapid alternations in hue, luminance, size, or shape of moving objects. They also showed that the perceived rate of alternation decreased for moving elements using a matching task of apparent flicker with stationary stimulus. These authors suggested that this reduction of visibility of the flicker could be due to the limited time each stimulus spent within a given receptive field—too brief to trigger a preferential response from flicker-tuned cells that could distinguish steady from flickering stimuli. Despite this "silencing" of the flicker for the moving stimulus, the authors suggested—citing a conference abstract of our work here—that the flicker may become visible if observers attended to individual disks. However, they did not directly investigate the effect of attention, whereas the focus of the present study is specifically this effect of attention to the moving, flickering target.

Visual spatial attention prioritizes information at the selected location improving its sensitivity (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Matsubara, Shioiri, & Yaguchi, 2007; Shioiri, Yamamoto, Kageyama, & Yaguchi, 2002), recognition accuracy (Eriksen & St James, 1986; LaBerge, 1983; Mackeben & Nakayama, 1993; Yeshurun & Carrasco, 1999) and shortening processing time (Carrasco & McElree, 2001; Hikosaka, Miyauchi, & Shimojo, 1993; Posner, Snyder, & Davidson, 1980) relative to stimuli presented at locations to which attention has not been initially allocated. We might expect that attention to a moving stimulus would help detect whether the stimulus is flickering or not. But attention can be focused on a target in at least two different ways: voluntarily (endogenous) attention (Posner et al., 1980) by directing attention to the target's location, and following it if it moves; or involuntarily (exogenous) attention (Jonides, 1981; Theeuwes, 1991; Yantis & Jonides, 1984) where an abrupt, salient feature draws attention to a target. One property that is quite efficient at drawing attention to a stimulus is motion or flicker. A target that is flickering among other nonflickering stimuli can be identified rapidly without having to search for it (Royden, Wolfe, & Klempen, 2001; Verghese & Pelli, 1992). Although attention may be drawn to transient stimuli, it may not always facilitate the processing of temporal properties of that stimulus (Bocanegra & Zeelenberg, 2011; Bush & Vecera, 2014; Yeshurun & Hein, 2011; Yeshurun & Levy, 2003).

In this report, we present multiple stimuli that are moving with one that is flickering. We investigate the effect of the speed of the motion on the threshold for detecting the flicker. We also cued the target in some conditions to see the effect of endogenous attention on the target. However, because of the salience of flicker, the cue may not facilitate the detection of flicker until the attentional requirements of the task are quite high. Our data bear out this possibility.

Experiment 1: Temporal frequency

Experiment 1 measured the contrast threshold for detecting luminance modulation of a moving target. To investigate the effect of attention, we compared the sensitivity between cue and no-cue conditions. The target was one of six disks moving circularly around a fixation point, and in the cue condition, a 100% valid cue indicated the target at the beginning of each trial. Temporal frequency was varied over seven values and the measurements were repeated with five different speeds of the moving targets.

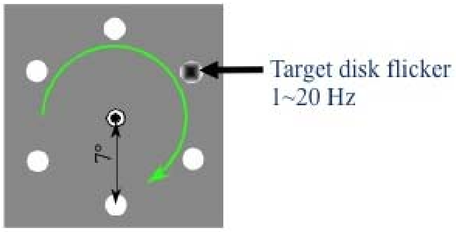
Method

Stimulus

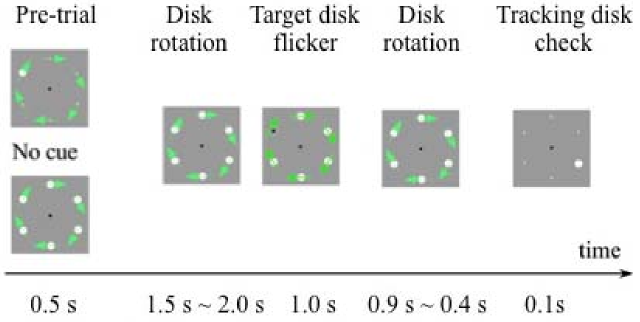
Figure 1 shows the stimulus configuration and the sequence of a trial. The moving stimulus was a white disk with a diameter of 1.1° (51 cd/m^2) on a gray background (28 cd/m^2). The disks moved along a circular path with a radius of 7° while the observer fixated on the center of the circle. The target disk changed its luminance sinusoidally at a given temporal frequency for 1 s, and the contrast modulation varied depending on the observer's response. All disks moved at the same speed in the same direction (clockwise or counterclockwise). The speed of the moving disks was 0, 0.08, 0.17, 0.33, or 0.67 revolutions per second (rps) (0°/s, 30°/s, 60°/s, 120°/s, or 240°/s in terms of rotation angle or 0°/s, 3.8°/s, 7.5°/s, 15.0°/s, or 30°/s in terms of the linear motion in visual angle). The flicker temporal frequency was 1, 2, 4, 8, 10, 16, or 20 Hz. Luminance of the target disk was modulated around a constant luminance (i.e., 51 cd/m^2) with variable contrast values.

Procedure

We used cue and no-cue conditions to manipulate the attentional state of the observer. In the cue condition, the size of the nontarget disks in the pretrial display (diameter of 0.28°) was smaller than that of the



(a) Stimulus



(b) Trial sequence

Figure 1. Stimulus (a) and trial sequence (b). One of six disks flickered and the observer was asked to detect the flicker. The disks moved at a fixed speed in each session.

target disk (1.1°). All disks were identical in size (1.1°) during the trial itself. In the no-cue condition, all disks had the same size in the pretrial and trial displays. The observers were instructed to track the target in the cue condition attentively while fixating at the central spot so that they could identify the contrast modulation (i.e., flicker) more efficiently. In contrast, in the no-cue condition, the observers were instructed to distribute their attention to cover the whole stimulus field to detect the disk with flicker.

Contrast threshold was measured with a staircase procedure. The pretrial display with moving disks was presented for 0.5 s, and then the trial started with continuous disk motion. The disk flicker was presented with a random start between 1.5 and 2 s after the end of the 0.5-s pretrial. The disks stopped after moving for a period between 0.9 and 0.4 s, depending on the duration of the motion before flicker began, so that the total time of disk motion was 3.9 s in all trials. The observer responded by pressing one of two keys, indicating whether they detected flicker in a disk (Yes/No task for flicker presentation). According to the response, stimulus contrast was determined for the next trial. A session ended with contrast reversals of 14 times and last four reversals were averaged to obtained threshold. The sensitivity found in the stationary condition confirmed that the subjective judgment was reliable for our observers in the present conditions. Although this does not rule out possible effect of criterion bias in the Yes/No task when attention changes sensitivities, we assume in this report that the difference between the cue conditions can be attributed to the sensory difference due to attention state because there is no particular reason to believe that criterion differs between cue and no-cue conditions. The influence of cue condition, or attention, on the criterion itself is an interesting issue that could be addressed in future studies.

At the end of each trial, the disks stopped and the target disk was indicated by a size difference (all the nontarget disks were reduced to 0.28° diameter) for 0.1 s. If the disk indicated as the target was not the one that the observer had tracked, the observer pressed a key to cancel the trial. The condition was repeated with the same contrast in the next trial with a different target disk. Observers had training sessions prior to the experiment to familiarize themselves with the procedure, and in the main experiments, they canceled only a few trials even with the fastest motion used (0.67 rps). We did not analyze tracking performance, but previous studies showed that attention is appropriately controlled with this tracking technique both with continuous motion as in the present stimulus (Shioiri, Cavanagh, Miyamoto, & Yaguchi, 2000; Shioiri, Yamamoto, Oshida, Matsubara, & Yaguchi, 2010) and with apparent motion with attentive tracking (Cavanagh, 1992; Matsubara, Shioiri, & Yaguchi, 2007; Shioiri et al., 2000; Verstraten, Cavanagh, & Labianca, 2000; Verstraten, Hooge, Culham, & Van Wezel, 2001).

Observers

One author and four observers naive to the purpose of the experiment participated in the experiment. All observers had normal or corrected-to-normal visual acuity.

Results and discussion

Figure 2a shows the contrast sensitivity averaged over five observers and Figure 2b and c shows results of individuals. We applied a three-way repeated measure analysis of variance (ANOVA; cue/no-cue, rotation speed, and flicker temporal frequency) to contrast sensitivity in log units, and the test showed that all the main effects were significant, $F(1, 4) = 17.14$, $p < 0.05$; $F(4, 16) = 216.43$, $p < 0.001$; $F(6, 24) = 49.36$, $p < 0.001$, and that the interactions were significant between cue effect and speed and between speed and temporal frequency, $F(4, 16) = 9.95$, $p < 0.001$ and $F(24, 96) = 12.53$, $p < 0.001$.

The no-cue trials show that sensitivity to flicker decreases dramatically when the stimuli are moving, dropping by a factor of 10 between the stationary and the 0.67-rps motion condition (for the 10-cps flicker).

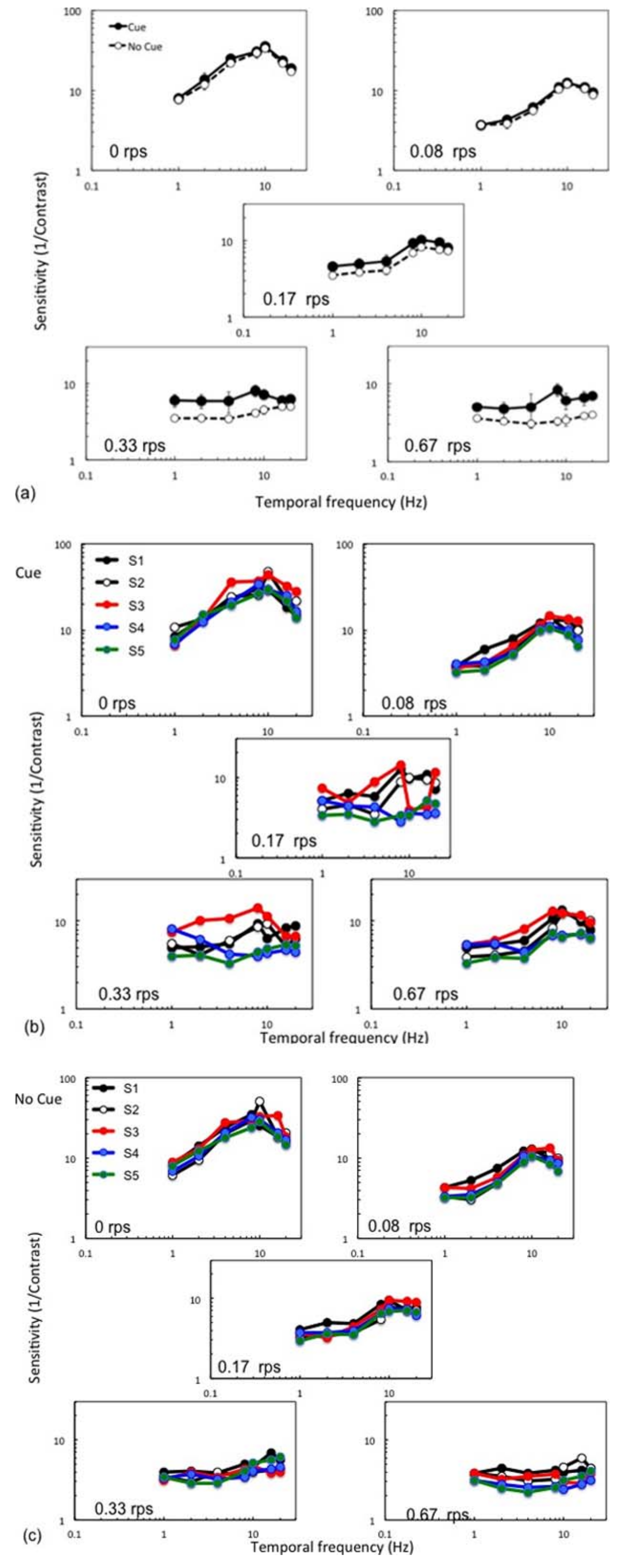


Figure 2. Contrast sensitivity as a function of temporal frequency for different speed conditions. (a) Filled circles indicate the sensitivity in the cue condition, and open circles indicate the sensitivity in the no-cue condition. Error bars indicate the standard error of mean across observers. (b) Individual results for the cue condition. (c) Individual results for the no-cue condition.

The contrast sensitivity function also changes from bandpass for stationary stimuli, with a peak at 10 Hz, to flat at 0.67 rps. These results indicate a switch from typical flicker detection, which is highly sensitive and optimal around 10 Hz (de Lange, 1958) to a very different process that has very poor sensitivity and little or no selectivity for temporal frequency, at least within the range tested here. The response in this case may rely on the detection of a luminance difference across locations. Since the light and dark parts of the sinusoidal flicker do not overlap when the disks move very fast, local stimulation has only a single luminance value. Without the specialized detectors to aid in detecting local flicker, this much less efficient, single pulse detection or cross-location comparison would not show differences for different temporal frequencies until the speed was slow enough to activate local flicker detection. This indifference to speed when detection requires a cross-location comparison may be the origin of the flat contrast sensitivity function at higher rotation rates.

There is also a change in the effect of attention when the targets move. When the disks were stationary or moving slowly (<0.08 rps), there was little or no attentional benefit for cued trials relative to no-cue trials. However, a robust attentional benefit was found for stimuli moving faster than 0.17 rps, and the difference between the cue and no-cue trials grew larger as the speed increased. We used the ratio between cue and no-cue conditions as an index of effect of attention. The benefit of attention for flicker detection is clearly shown for stimuli moving with higher speeds. In Figure 3, the attentional facilitation ratio, averaged over temporal frequencies, shows this increased effect at faster speeds.

In the no-cue conditions, observers were instructed to spread their attention over the whole field, but it is possible that they adopted other strategies to detect the flickering target, especially at high speeds. At the slow speeds, the flicker would be quite salient and visible even with attention spread across the field. At higher speeds, however, observers may have switched attention from one stimulus to the next to discover the flickering target. If they did so, the data should reveal an increase in threshold variability with speed. This is because the target was only present for 1 s, so sequential sampling would not be fast enough to reach all six items before the target disappeared. According to previous psychophysical studies, the time required to shift attention to a new location is on the order of several hundreds of milliseconds (Egeth & Yantis, 1997; Kashiwase, Matsumiya, Kuriki, & Shioiri, 2012; Kashiwase et al., 2013; Wright & Ward, 2008). This should produce both a loss of sensitivity (which is seen) and an increase in variability as there would be an increasing fraction of trials on which the target is not

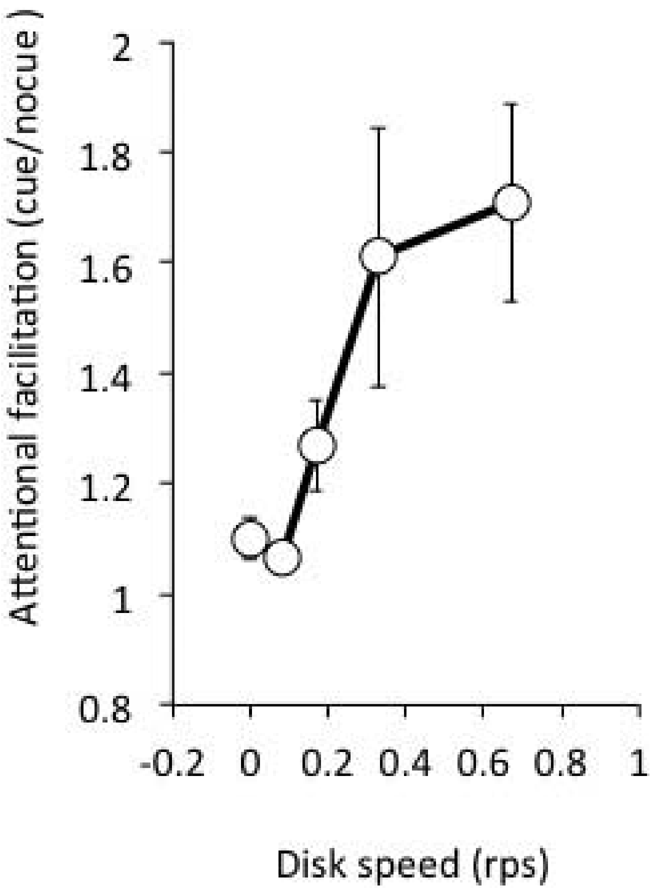


Figure 3. Attentional facilitation (cue/no-cue) averaged over all temporal frequencies as a function of temporal frequency. Error bars indicate the standard error of mean across observers.

reported because it is not sampled, randomly perturbing the threshold estimates. However, the ratio of standard deviation of thresholds between cue and no-cue conditions does not increase at higher speeds; it decreases from 1.16 for 0 rps, to 0.24 for 0.67 rps (see smaller error bars for no-cue than for cue in the panel of 0.67 rps in Figure 2a). There is no clear evidence in the threshold variability to support sequential sampling of the moving items in the no-cue condition. Observers likely spread attention over the whole field in the no-cue condition, as was instructed.

Experiment 2: Temporal integration

In the second experiment, we investigated whether the higher sensitivity in the cue condition is due to an effect of attention on the temporal integration of stimulus signals, specifically the critical duration and rate of integration. The critical duration or the temporal summation limit is the time within which the mechanism that is responsible for the threshold integrates the corresponding signals. Here, the corresponding signal is luminance flicker. Since attention is known to facilitate temporal integration along the motion path of a tracked object (Cavanagh, Holcombe, & Chou, 2008; Holcombe & Cavanagh, 2008; Kahneman, Treisman, & Gibbs, 1992; Nishida, Watanabe, Kuriki, & Tokimoto, 2007), it is possible that this facilitation of integration contributed to the cue advantage in Experiment 1. In order to investigate this possibility further, we measured contrast sensitivity as a function of stimulus duration. Attentional facilitation of temporal integration, or more precisely spatiotemporal integration for moving objects, may increase the efficiency of temporal integration (the rate of integration) or the period over which integration occurs (the critical duration), or both.

Method

The method, stimuli, and observers were the same as in Experiment 1, with the exception of variable durations of stimulus presentation using only one test frequency and two disk motion speeds. We used an 8-Hz test flicker frequency at rotation speeds of 0 and 0.33 rps. Stimulus presentation duration was either 250, 500, 750, 1000, 1500, or 2000 ms. Since other temporal parameters were the same as in Experiment 1, the total period of a trial varied between 3.25 and 5 s.

Results and discussion

Figure 4 shows the contrast sensitivity as a function of stimulus presentation duration for the four combinations of cue versus no-cue and 0 versus 0.33 rps. We applied a three-way repeated-measure ANOVA (cue/no-cue, rotation speed, and presentation duration) to the contrast sensitivity in log units, and the test showed that all three main effects were significant, $F(1, 4) = 58.59$, $p < 0.01$; $F(1, 4) = 535.07$, $p < 0.001$; $F(5, 20) = 55.71$, $p < 0.001$, and that the three-way interaction was significant, $F(5, 20) = 5.79$, $p < 0.01$, as well as all the two-way interactions, $F(1, 4) = 43.50$, $p < 0.01$ between cue effect and speed; $F(5, 20) = 5.10$, $p < 0.01$ between cue effect and duration; and $F(5, 20) = 4.92$, $p < 0.01$ between speed and duration.

The sensitivity was higher at 0 rps than at 0.33 rps as in Experiment 1. There was a slight effect of the cue at 0 rps, whereas a large cue effect was seen at 0.33 rps, also consistent with Experiment 1. The sensitivity increased with presentation duration, reaching an asymptote somewhat beyond 1000 ms. This suggests that there is a critical duration of temporal summation, beyond which no signals are integrated.

We analyzed two indexes to examine the effect of attention. One is the period of temporal integration,

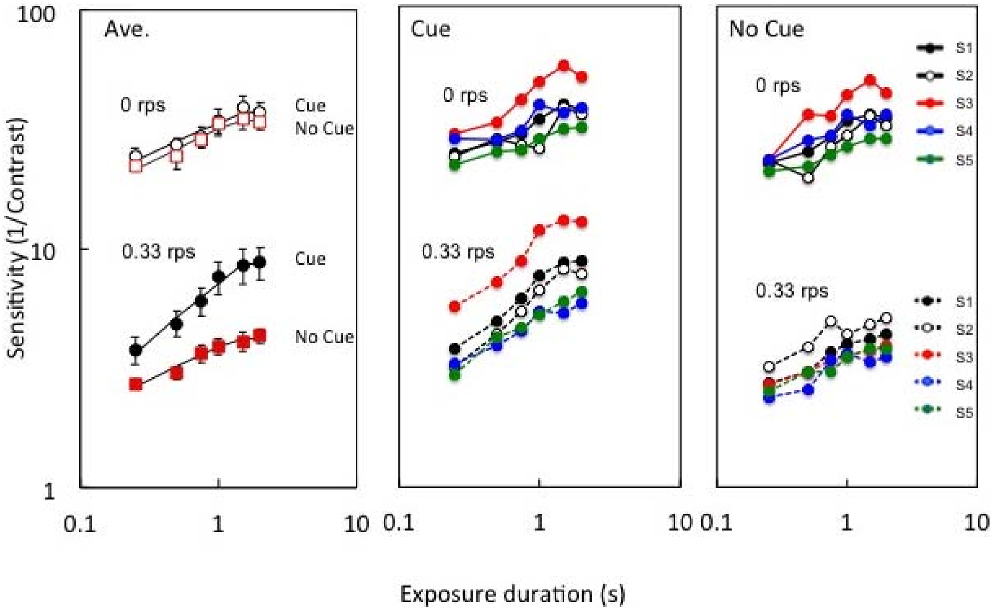


Figure 4. Contrast sensitivity as a function of stimulus presentation duration. Left: Open symbols indicate the 0-rps condition, and filled symbols indicate the 120-rps condition. Black circles indicate cue conditions, and red squares indicate no-cue conditions. Lines show the bilinear function fitted to the data for each condition. Error bars indicate the standard error of mean across observers. Middle: Individual results for the cue condition. Right: Individual results for the no-cue condition.

and the other is the efficiency of temporal integration. They were obtained by fitting a bilinear function to each data set. Since the results suggest that there is a critical duration of temporal integration, we used a linear function with parameters of slope and intersection for the first segment and a linear function with a slope of zero and a free parameter for the intercept for the second segment (i.e., $y = \text{constant}$). A test of goodness of fit with a χ^2 distribution for the approximation showed that the χ^2 value was no larger than 0.01 in any condition across all observers, which is much smaller than 1.15, the $p < 0.05$ criterion for 5 degrees of freedom in our fit. We took the intersection of the two linear segments as an estimate of the critical duration of temporal integration and the slope of the first linear segment as an estimate of the efficiency of integration. A clear difference was found in both indexes between cue and no-cue conditions for the disks in motion at 0.33 rps (Figure 5), whereas little difference was found in either index with stationary disks (the critical duration was 1723 ± 229 and 1677 ± 365 and the slope was 0.25 ± 0.10 and 0.27 ± 0.11 for cue and no-cue conditions). For the stimuli moving at 0.33 rps, the efficiency (slope) increased by 75.8% on average in the cue as compared to no-cue condition ($t = 10.80$, $p < 0.001$), while the critical duration increased from 1321 to 1526 ms ($t = 4.55$, $p < 0.02$). In contrast, no significant difference was found for either index in the 0-rps condition ($t = 0.63$, $p > 0.5$; $t = 1.07$, $p > 0.3$). The effect of attention on the efficiency and critical period of integration flicker detection was therefore found only when disks were moving.

The critical duration for temporal integration from our data (Figure 5) is about 1.5 s, and that corresponds to a half rotation (180°) at the 0.33-rps rotation speed. The period of 1.5 s is much longer than the typical value of 100 ms found for detecting luminance changes in many experiments (Ikeda & Boynton, 1965; Rashbass, 1970; Roufs, 1972). One of the possible explanations is the difference in stimulus features. Because the average luminance was constant over time (0 rps) or along the motion path (at 0.33 rps), the increase in sensitivity with presentation duration over more than one flicker cycle (125 ms) could be attributed to the temporal integration of a second or higher order feature, in this case flicker. Studies using higher order features such as texture (Gorea, Wardak, & Lorenzi, 2000; Ledgeway & Hess, 2002; Manahilov, Calvert, & Simpson, 2003) and motion (Burr & Santoro, 2001; Neri, Morrone, & Burr, 1998; Regan & Beverley, 1984; Shioiri & Cavanagh, 1992; Shioiri, Ito, Sakurai, & Yaguchi, 2002) have shown temporal integration much longer than 100 ms (sometimes as long as 3 s; Neri, Morrone, & Burr, 1998). The different critical durations between the previous and present experiment may also be attributed to the difference in stimulus configurations. Our flickering target was presented along with several distractors and the target and distractors were of relatively small size and presented in the periphery in comparison to standard measures of critical duration. We are not sure which of these

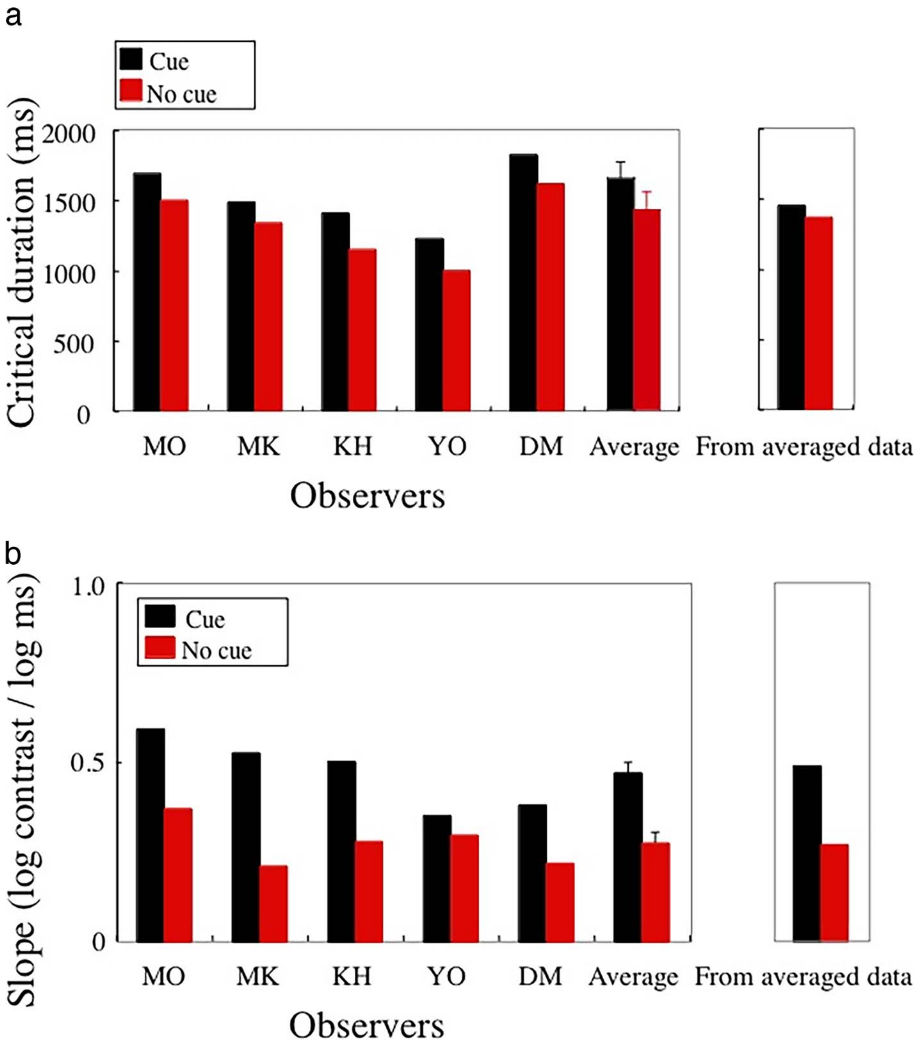


Figure 5. (a) The critical duration for temporal integration obtained from the fitted function to each data set in Experiment 2. Black bars indicate the cue conditions, and red bars indicate the no-cue conditions. Individual results and their average with standard errors across observers are shown. The rightmost data are the critical duration from the bilinear functions fitted to the average sensitivity results of all observers. (b) The slope of the first segment of the fitted function for cue (black) and no-cue (red) conditions. The slope reflects the efficiency of temporal summation in the condition. Notations are the same as in (a).

differences led to our relatively long period of temporal summation, and the examination of this question is left for future investigations.

Could the temporal integration across 1.5 s that we see be the result of probability summation? Probability summation here would reflect an increase of detection rate due to multiple chances to sample the signal over longer presentations (Watson, 1979) rather than an improvement in sensitivity. However, the effect of probability summation should increase with stimulus presentation duration without any asymptote, so our results showing a critical duration cannot be explained by probability summation (Masuda & Uchikawa, 2009; Watson, 1979). The results therefore indicate that the effects of attention cannot be explained solely by probability summation and suggest that attention facilitates flicker detection through a process that accumulates signals over a long (1.5 s) interval when the stimuli are moving.

General discussion

As had been suggested by Suchow et al.'s (2011) motion silencing, we find here a 10-fold loss in sensitivity to detect a flickering target when it is in motion. In addition, the effect of temporal frequency on sensitivity profile changed from bandpass, similar to that seen in many previous reports for stationary targets (de Lange, 1958; Kelly, 1984; Robson, 1966) to flat, indicating a wholesale change in detection strategy. In particular we suggest that the sensitive detection of flicker for stationary targets was mediated by local, frequency-tuned receptive fields (DeAngelis et al., 1993; Frishman et al., 1987; Tan & Yao, 2009); however, when the targets moved, the duration that the stimulus remained in any one receptive field decreased as the speed increased, reducing this contribution to detection. Observers may then have to resort to comparing lighter and darker portions of the target's moving trajectory. In particular, at the highest speeds, there was no spatial overlap between the target position for the peak and trough values of the 10-Hz flicker making their comparison possible.

The effects of cueing support this interpretation. Cueing had no effect on detection when targets were stationary or moved only slowly, suggesting that the flicker was very salient and detected without having to narrow attention to only the flickering item. Indeed, even though there were six targets and only one of them flickered, the sensitivity for this one target among six was comparable to reported sensitivity for isolated targets at the same eccentricity and size (Snowden & Hess, 1992). This indicates, as has been reported in visual search paradigms (Royden et al., 2001; Verghese & Pelli, 1992), that the flickering target draws attention and can be detected among other nonflickering stimuli without having to search for it—the additional nontargets do not add noise to the detection process for targets that have little or no motion. It should be noted that effect of attention itself is not likely very different between moving objects and stationary ones. Shioiri and Matsumiya (2009) reported similar attentional modulation on motion aftereffect (MAE) of moving gratings (either 0.2 or 2 c/°) for the temporal frequency range from 0.6 to 20 Hz. It is also true that attention increases neural response to flickering stimulus at a location, as has been shown by steady state visual evoked potential studies (Kashiwase et al., 2012; Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007; Muller et al., 1998).

When the targets moved at medium to high speeds, the results were qualitatively different, and now cueing had a large effect on sensitivity. We assume that the flicker, spread out as light and dark segments along the target's trajectory, was no longer sufficiently salient to automatically attract attention and that detection now required scrutiny. When the cue specified the target that was flickering, attention could track it and filter out the nontargets. When the target was not cued, observers had to spread attention over all six items and the extra noise from the nontargets would degrade the detection process.

We assumed that the observers' eye fixation were stable during a trial in this setup on the basis of a previous study showing little effect of eye movements in an attentive tracking experiment similar to the present one (Verstraten et al., 2001). We also measured eye movements to examine how stable fixation is in the condition of Experiment 1 with the task of flicker detection. Five new observers were asked to track a moving target to detect flicker while recording eye movements (EyeX, Tobii Technology, Dandeyd, Sweden). There were two conditions: 8-Hz flicker with 15% contrast and no-flicker condition under 0.67-rps rotation of disks. The observers had 10 trials of each condition, which were randomly mixed in a session. The deviation of the eye position from the fixation point was 0.38° (±0.1°) on average across observers and the percentage of correct responses was 78% (±0.15%). This measurement confirmed the stability of fixation in the present experimental conditions.

In Experiment 2, we found an effect of attention on temporal integration over intervals up to 1.5 s for the moving targets (but not for stationary ones). Cueing substantially increased integration efficiency (the rate of signal accumulation) and had a small but significant effect on the integration duration (the time over which the signal is accumulated). When the cue specified the target that was flickering, attention could track it and enhance integration of visual information along the motion trajectory. Although we have no specific proposals for the underlying mechanisms for this attention effect, there are two possible interpretations. First, the increase of the slope of efficiency of integration when the target was attended may be interpreted as an increase of the gain and speed typically attributed to attention in the literature. They may be the consequence of an increase of the output gain of the flicker detection process along the motion pathway. Increase of gain is one of typical effect of attention, but in our case here, the attentional focus is assumed to move with object (Horowitz et al., 2004; Shioiri & Cavanagh, 2000; Shioiri et al., 2002). The increase of the slope may also be interpreted as a consequence of an increase in processing speed (Carrasco & McElree, 2001; Nakayama & Mackeben, 1982; Posner, 1980). Faster processing can access more information from a moving object at a certain location. Second, the increase in integration duration caused by attention may differ from the increase in gain and speed. Instead, it may be related to the spatial spread of attention. In the no-cue condition, observers were instructed to attend over the whole stimulus area, whereas in the cued condition, they focused on small area. The duration of integration may be longer for smaller attended areas.

Yeshurun and Levy (2003) have reported that attending to the target location reduced observers' ability to detect a temporal gap, and this was confirmed by subsequent studies (Bocanegra & Zeelenberg, 2011; Bush & Vecera, 2014; Rolke, Dinkelbach, Hein, & Ulrich, 2008; Yeshurun, 2004; Yeshurun & Hein, 2011). These authors suggested that an attentional mechanism that favors parvocellular over magnocellular neurons enhanced spatial resolution and decreased temporal resolution. Our results with the stationary disks showed no evidence for a decrease in performance with cueing over the temporal frequencies we used (and no evidence for an increase either). One critical difference between their studies and ours was that they used exogenous cueing to attract attention, whereas we used an endogenous cue. The different effect of exogenous and endogenous attention on temporal perception has been studied for temporal order judgments. Hein, Rolke, and Ulrich (2006) showed that temporal order judgments were impaired only when exogenous attention was triggered. The present results are consistent with this difference between exogenous and endogenous attention where endogenous attention does not impair contrast threshold even for high temporal frequency flicker.

The small effect of cueing in stationary disk conditions is consistent with the automatic attraction of attention to a transient stimulation. If flicker in a disk attracts attention, it can be efficiently detected independently of the cue location. The results of Experiment 2 show a slight difference between the cue and no-cue conditions. This difference is equivalent to the cost of a 250-ms shorter presentation in the 1-s condition, and this value may be regarded as the time required to shift attention to the flickering disk in the no-cue condition. The estimation of 250 ms for the shift of attention is within the estimation of attention shift in the literature, and therefore the small effect of cue conditions for stationary disks can be attributed to attention attraction by flicker stimulus. It should be noted, however, that this interpretation assumes that flicker attracts attention before detection of the flicker and that the attention that is attracted decreases the contrast threshold of flicker detection.

In summary, the present experiments revealed that sensitivity to flicker decreased dramatically when the flickering target was in motion, a change we attribute to the local nature of the most sensitive receptive fields mediating detection. Cueing had no effect for stationary targets, but once they were in motion, attention facilitated detection of luminance changes over the entire temporal frequency range that we tested. We suggest that the flicker of a moving target must be detected by noticing luminance differences spread over space and that this is best accomplished when spatial attention can focus on the known target. We identified two aspects of the effect of attention on flicker detection: an increase in the efficiency and duration of signal integration along the motion trajectory of the attended object. We conclude that focused attention filters out the other stimuli, and so enhances the integration of luminance change signals along the motion trajectory.

Keywords: attention, motion, temporal summation, temporal frequency, flicker

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